New SAW-Convolver Demodulation Technique Using Costas–Loop Synchronization for High-Speed Spread-Spectrum Signal

Mitsutaka Hikita, *Senior Member, IEEE*, Chisaki Takubo, and Kengo Asai

***Abstract*—A new synchronous-demodulation method for a high-speed spread-spectrum (SS) signal, which combines a surface acoustic wave convolver with a Costas–Loop circuit has been proposed. From the convolver, in-phase and quadrature-phase components of the correlated signal can be directly derived. A control voltage obtained by a Costas–Loop circuit adjusts the frequency and phase of a local-oscillation (LO) signal to those of the SS signal. Thus, in the receiver, synchronization of the LO signal and the received signal can be carried out independently of the transmitter. A quadrature phase-shift keying SS signal with 9 Mb/s and 60 Mc/s has been successfully demodulated using this method.**

***Index Terms*—Costas–Loop synchronization, SAW convolver demodulation, spread-spectrum applications.**

I. Introduction

VERY high-speed, i.e., 1–30 Mb/s, spread-spectrum (SS) communications will be used in future wireless local area networks (WLANs) [1]–[3]. Surface acoustic wave (SAW) matched filters [4] and SAW covolvers [5] were investigated to be used in SS communications. We have already proposed the high-performance SAW convolver, which has self-temperature-compensation characteristics regardless of temperature coefficients of delay (TCDs) of strongly piezoelectric substrates [6]. Both binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) can be used, and baseband demodulation signals can be directly derived as output signals.

When demodulating an SS signal using a SAW convolver in a receiver, synchronization of the local-oscillation (LO) signal and the received signal is very important. We have developed a new synchronous-demodulation method for an SS signal by combining a SAW convolver with a Costas–Loop [7] circuit. To demodulate a QPSK-modulated SS signal [8], an in-phase component, i.e., $\cos\theta$, and a quadrature-phase component, i.e., $\sin\theta$, from the convolver are added, subtracted, and multiplied mutually, which produces a $\sin 4\theta$ signal. This $\sin 4\theta$ signal controls a voltage-controlled temperature-compensated crystal oscillator (VC-TCXO) via a feedback mechanism to force $\sin 4\theta$ to zero. This is because the VC-TCXO provides the standard signal that determines the frequency of the LO signal by a phase-locked-loop (PLL) circuit [9]. Thus, zero means that the LO signal and the received SS signal are synchronized.

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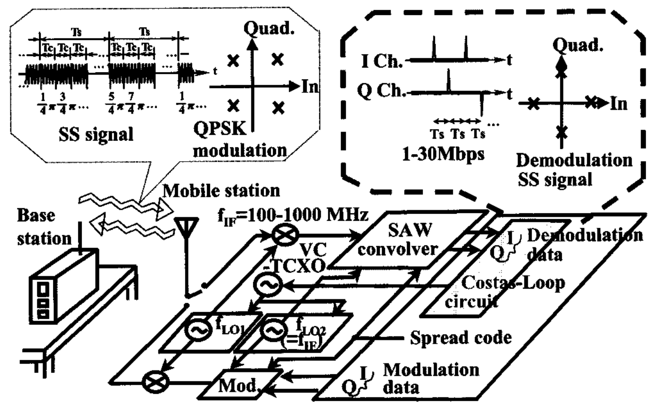

Fig. 1. High-speed SS communications (WLAN, etc.) and block diagram of a radio transceiver. Voltage from Costas–Loop circuit controls VC-TCXO.

A schematic block diagram of a high-speed SS transceiver that uses the proposed SAW-convolver demodulation technique with a Costas–Loop circuit is shown in Fig. 1. Received RF SS signals are down converted to an IF by mixing with the first LO (LO1) signal. The IF signals and the second LO (LO2) signal are supplied to the SAW convolver, and I- and Q-channel data can be directly derived from the convolver via the Costas–Loop circuit.

In this paper, we will first briefly illustrate the SAW convolver. Next, we will explain the proposed demodulation method using the Costas–Loop circuit. Finally, we will show experimental results that confirm the validity of the new method. In the experiments, we have successfully demodulated a QPSK-modulated SS signal, which has a high speed of 9 Mb/s, and a wide SS of 60 Mc/s using a 13-chip Barker code [10] as the spreading code.

II. Fundamental Structure of SAW Convolver

The most important problem in SAW delay lines for SS communications is due to the TCD of the SAW. Changes in SAW velocity cause phase differences between early and late chips within a single SS symbol. Thus, we invented a new temperature-compensated SAW delay line. The fundamental structure of the SAW convolver using these SAW delay lines is shown in Fig. 2 [6]. Three SAW delay lines with $i = 1$, 2, and 3 are used. The upper and lower delay lines are mutually out of phase by $\pi/2$, as shown in Fig. 2. The middle one, i.e., $i = 1$, is used for the SS signal, and the other ones, i.e., $i = 2$ and 3, respectively, are used for the LO2 signal of Fig. 1. In order

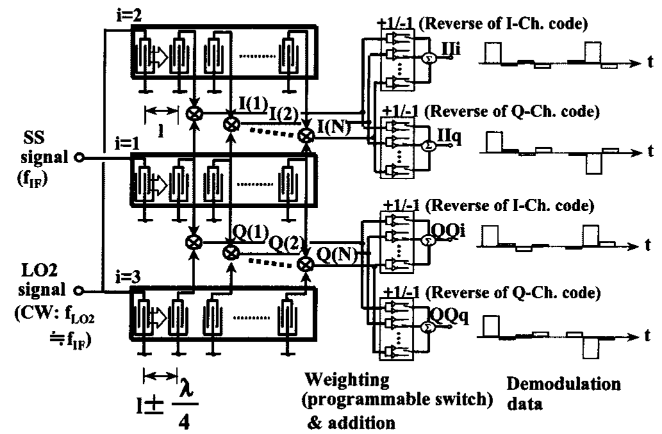

Fig. 2. Fundamental structure of temperature-compensated SAW convolver and waveforms of demodulated data.

to compensate for temperature characteristics, electrical lengths between the inter-digital transducers (IDTs) are equal for all three delay lines. SS signals and LO2 signals from the output IDTs are mixed, which provides mixer-output signals with a frequency of $f_{\rm IF} - f_{\rm LO2}$, as shown in Fig. 2. When the LO signal is completely synchronized with the receiver SS signal, i.e., $f_{\rm LO2} \approx f_{\rm IF}$, output signals from the mixers have no carrier-frequency component, which means that the baseband signals, i.e., $I(i)$ and $Q(i)$, can be directly derived from the mixers, as shown in Fig. 2.

The in-phase components from the mixer, i.e., $I(i)$ and the quadrature-phase components, i.e., $Q(i)$, are weighted by $+1$ or -1 in reverse order to the I- and Q-channel spreading codes by using switches. Due to the programmable switches, the SAW convolver can be used for arbitrary spreading codes. After weighting, all output signals for each channel are added, which provides the correlated output signals, i.e., IIi, QQi and IIq, QQq.

III. Demodulation of QPSK-SS Signal Using SAW Convolver

A. Cheating Method for Synchronization

A schematic block diagram of the measurement system of the cheating method is shown in Fig. 3. In a transmitter, a continuous wave (CW) signal is generated from a signal generator (SG). As precisely explained in a later experiment, about 350 MHz is used in this case, and for simplicity, the down converter of Fig. 1 is not used in the receiver. Therefore, 350 MHz corresponds to $f_{\rm LO2}$ of Fig. 1. As shown in Fig. 3, the CW signal is divided into two paths within the transmitter. One path goes to the orthogonal modulators, which produce a QPSK-SS signal using two baseband function generators that provide the I- and Q-channel spreading codes and also the data. The other path is directly connected to the receiver via a cable, which provides the LO signal to the SAW convolver, as shown in Fig. 3. In general, this kind of synchronization could be called a cheating method. The transmitter and receiver are ideally locked. The synchronization of the phase between the LO and receiver SS signals can be also established by tuning a phase shifter between the transmitter and receiver of Fig. 3. Thus, the output signals from the convolver, i.e., IIi, QQi and IIq, QQq, correspond to the I- and Q-channel data, respectively.

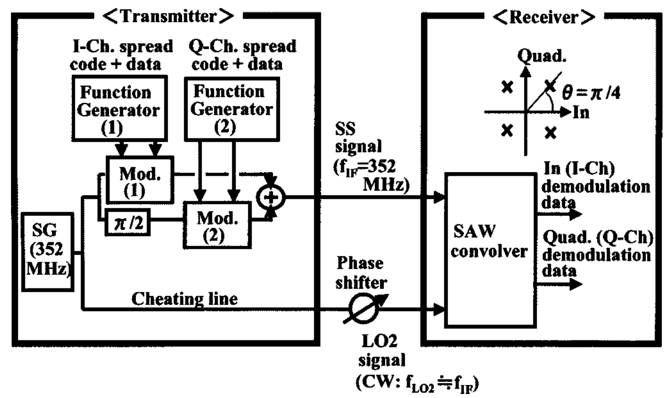

Fig. 3. Measurement system for SAW convolver using cheating method. SG is used to generate the SS signal in the transmitter and to provide the LO signal to receiver.

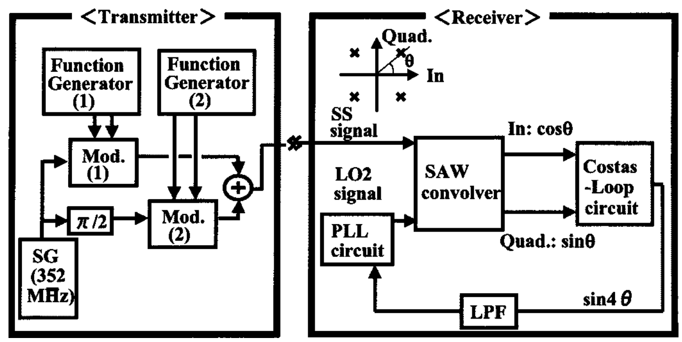

Fig. 4. Measurement system for SAW convolver using Costas–Loop circuit. Synchronous LO signal is generated independently of the transmitter.

B. Costas–Loop Circuit Method for Synchronization

The receiver and transmitter are to operate independently in actual communications. Without synchronization, the frequencies of the received SS signal and the receiver LO signal will be different to each other. In this condition the SAW convolver cannot provide correct data.

We have proposed a new synchronous-detection method to demodulate an SS signal by combining the SAW convolver with the Costas–Loop circuit. A schematic block diagram of the measurement system using a Costas–Loop circuit [7] is shown in Fig. 4. In the experiments, an SS signal generated from an independent transmitter is supplied to the convolver of the receiver via a cable. To generate the QPSK-SS signal in the transmitter, we can use the same orthogonal modulators as used in the cheating method. About 350 MHz is also used in this case and, for simplicity, the down converter is not used in the receiver. Therefore, 350 MHz also corresponds to $f_{\rm LO2}$ of Fig. 1. The LO2 signal from the VCO, which is locked to a VC-TCXO using a phase-locked loop (PLL) circuit, is also supplied to the convolver of the receiver, as shown in the figure.

From the convolver, we can obtain the in-phase and quadrature-phase components of I- and Q-channel data by using the phase of LO2 signal as a standard. However, in order to determine real I- and Q-channel data, we must adjust the frequency and phase of the LO2 signal to the received SS signal. The

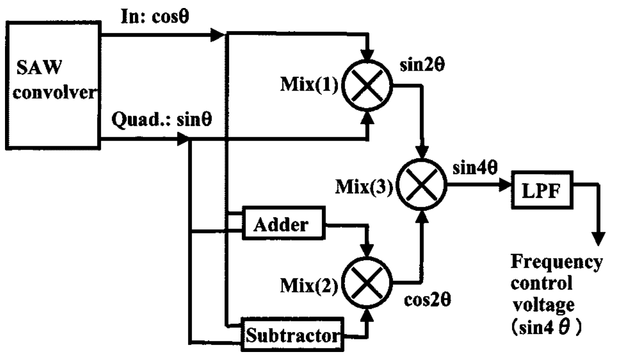

Fig. 5. Costas–Loop circuit. Control voltage to VC-TCXO is obtained from $\sin 4\theta$ after low-pass filtering.

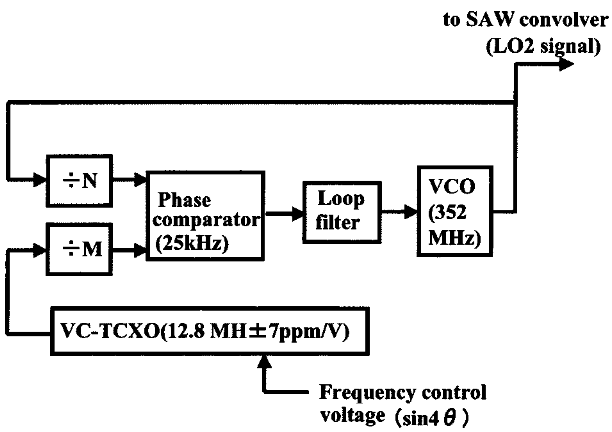

Fig. 6. PLL circuit. Frequency and phase of the VCO are adjusted to those of the VC-TCXO.

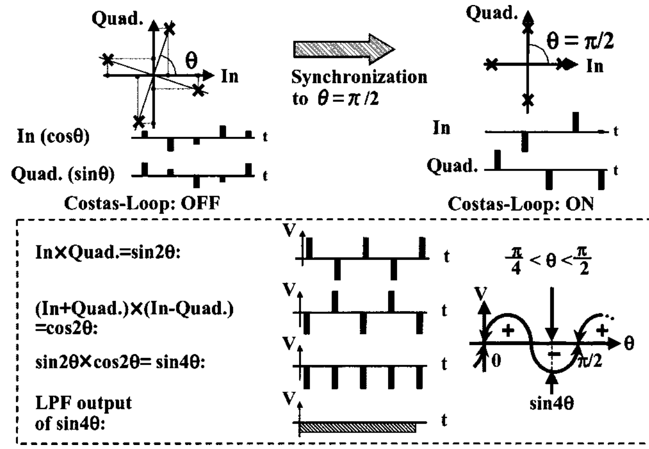

Fig. 7. Constellation diagram with Costas–Loop circuit in ON/OFF states, and waveforms for each section within Costas–Loop circuit.

Costas–Loop circuit using in-phase component (In) and quadrature-phase component (Quad.), i.e., $\cos\theta$ and $\sin\theta$, respectively, is shown in Fig. 5, where θ is defined by $\theta = \tan^{-1}$ (In/Quad.), as shown in an upper right-hand-side constellation diagram of Fig. 4. In the case of QPSK-SS communications, the operations $4 \times (\cos\theta + \sin\theta) \times (\cos\theta - \sin\theta) \times \cos\theta \times \sin\theta = \sin 4\theta$ is conducted by an add circuit, a subtract circuit, and mixers. As shown in Fig. 5, $\cos\theta$ and $\sin\theta$ are supplied to Mix(1), Adder and Subtractor, which produce $\sin 2\theta, \cos\theta + \sin\theta$, and $\cos\theta - \sin\theta$, respectively. Therefore, $\cos 2\theta$, the multiple of $(\cos\theta + \sin\theta)$, and $(\cos\theta - \sin\theta)$, can be obtained from Mix(2). Thus, $\sin 4\theta$ can be obtained from Mix(3) by multiplying $\sin 2\theta$ and $\cos 2\theta$. The control voltage for the VC-TCXO can be derived from $\sin 4\theta$ after low-pass filtering, as shown in Fig. 4. This voltage controls the frequency of the VC-TCXO so that $\sin 4\theta$ becomes zero. This is because the VC-TCXO provides the standard signal that sets the frequency of the LO2 signal by using the PLL circuit.

A PLL circuit [9] used in the later experiment is shown in Fig. 6. We used a VC-TCXO with the controlled-frequency range of 12.8 MHz $\pm$7 ppm/V. The output signals from the VC-TCXO and the VCO are supplied to frequency dividers with $M = 512$ and $N = 14080$, respectively. Two signals from the frequency dividers are applied to a phase comparator, which produces a voltage corresponding to the phase difference between two signals. The voltage from the phase comparator is applied to the frequency-control terminal of the voltage-controlled oscillator (VCO) via a loop filter, a kind of low-pass filter. This feedback process makes the frequency and the phase of the VCO lock to the VC-TCXO.

The signal waveforms for each section within the Costas–Loop circuit are shown in Fig. 7. When the Costas–Loop is OFF, θ is not fixed, thus, real demodulation data cannot be obtained, as shown in the upper left-hand-side figure. When the Costas–Loop is ON, each section within the circuit has a voltage related to the value of θ, as shown in the lower part of Fig. 7. For example, when $\pi/4 < \theta < \pi/2$, $\sin\theta$ becomes negative, thus, a negative control voltage is applied to the VC-TCXO after low-pass filtering, as shown in the lower figure. Due to this control voltage, the frequency of the VC-TCXO will decrease, until $\sin 4\theta = 0$, i.e., $\theta = \pi/2$, as shown in the upper right-hand-side figure. Thus, complete synchronization of the LO2 signal and received signal can be achieved.

IV. Experimental Verification for New Demodulation Technique

A. Theoretical Estimates

First, we calculated the waveforms of the correlated output from the SAW convolver, as shown in Fig. 8. We used a 13-chip Barker code [10] as the spreading code for both I- and Q-channels. We simulated the transmitted I- and Q-channel data sequences, which were $+1-1-1+1,\ldots$ and $+1+1-1-1,\ldots$, respectively. In the case of the cheating method, the positions in a constellation diagram, i.e., (a)–(d), and the estimated output waveforms are shown in the left-hand-side part of Fig. 8. Due to the phase relation $\theta = \pi/4$, the demodulated in-phase and quadrature-phase components, i.e., In and Quad., are identical to the respective transmitted data sequences.

When using the Costas–Loop circuit, due to the phase relation $\theta = \pi/2$, as shown in the constellation diagram, the demodulated In and Quad. are estimated as $0 - 1\ 0 + 1,\ldots$ and $+1\ 0 - 1\ 0,\ldots$, respectively as shown in the right-hand-side part of Fig. 8. Real I- and Q-channel data can be obtained from the operations (In $+$ Quad.) and $-$(In $-$ Quad.), i.e., $+1-1-1+1,\ldots$ and $+1+1-1-1,\ldots$, respectively. These are the same as the transmitted data, as shown in the lower part of Fig. 8.

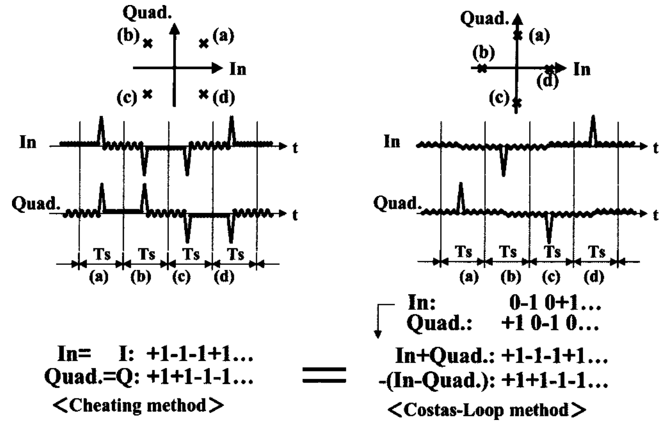

Fig. 8. Constellation diagram and estimated waveforms from SAW convolver. Comparison between cheating method and Costas–Loop circuit method.

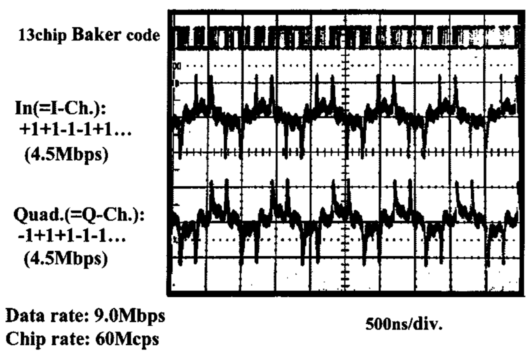

Fig. 9. Demodulated waveforms using the cheating method, as shown in Fig. 3.

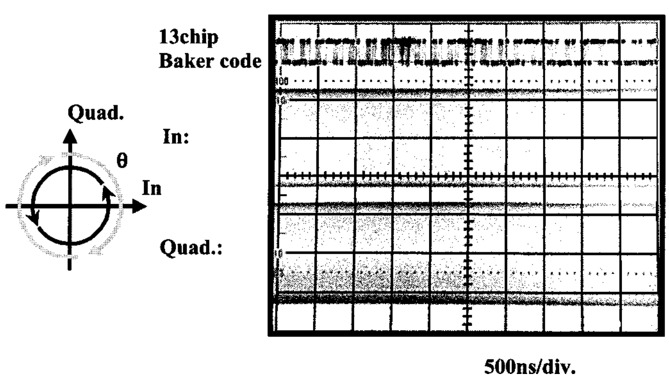

Fig. 10. Output waveforms from SAW convolver with Costas–Loop circuit in OFF state.

B. Experimental Results

The experimental results using the methods explained in Section III will be presented. The waveforms of demodulation data from the SAW convolver using the cheating method are shown in Fig. 9. The transmitted I- and Q-channel data sequences were the same as those used in the theoretical estimates. Data identical with those shown in the left-hand-side part of Fig. 8 have been demodulated.

As a comparison, the output waveforms from the SAW convolver with the Costas–Loop circuit not operating are shown in Fig. 10. Due to the indefinite relations for both frequency and phase between the received SS and LO2 signals, real I- and

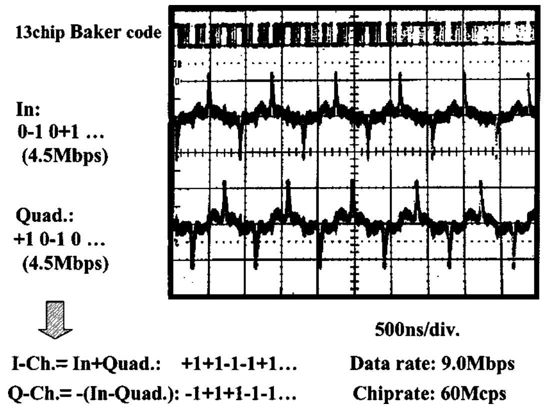

Fig. 11. Demodulated waveforms from SAW convolver using Costas–Loop synchronization. I- and Q-channel data can be obtained from operations (In $+$ Quad.) and $-$(In $-$ Quad.), respectively.

Q-channel data cannot be obtained from the convolver, as shown in Fig. 10.

Demodulated waveforms from the SAW convolver with the Costas–Loop circuit in ON state are shown in Fig. 11. In this case, In and Quad., i.e., $0-1\ 0+1,\ldots$ and $+1\ 0-10,\ldots$, respectively, have been successfully demodulated. These are the same as the numerical estimates (Fig. 8). From the operations (In $+$ Quad.) and $-$(In $-$ Quad.) respectively, I- and Q-channel data identical to those shown in Fig. 9 can also be obtained. Each of the I- and Q-channels provides 4.5 Mb/s. The symbol length is 0.22 μs and the chip length is 0.0166 μs. Therefore, it has been shown that the SAW convolver can be used to demodulate 9 Mb/s with a 60-Mc/s QPSK-SS signal by using a synchronous-detection method based on the Costas–Loop circuit.

V. Conclusion

In this paper, we have proposed a new synchronous-detection method for demodulation of an SS signal using a SAW convolver combined with a Costas–Loop circuit. In the receiver, synchronization of the LO signal and the received SS signal can be established independently of the transmitter. Basic experiments with 9 Mb/s and 60 Mc/s show that this method will be very useful for the demodulation of SS signals used in future high-speed SS communications.

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